

ENERGETIC CHARGED PARTICLES IN SATURN'S MAGNETOSPHERE:
VOYAGER 1 RESULTS

ABSTRACT

Voyager 1 provided the first look at Saturn's magnetotail and at its magnetosphere during relatively quiet interplanetary conditions. This initial report discusses energetic particle populations of the outer Saturnian magnetosphere, absorption features associated with Titan and Rhea, and compares these Voyager 1 observations with Pioneer 11 data of a year earlier. The trapped proton fluxes had soft spectra, represented by power laws in kinetic energy, E , as $E^{-\gamma}$, with $\gamma \sim 7$ in the outer magnetosphere, $\gamma \sim 9$ in the magnetotail. Structure associated with the magnetotail was observed into $L \sim 10$ on the outbound trajectory. The proton and electron fluxes in the outer magnetosphere and in the magnetotail were variable and appeared to respond to changes in interplanetary conditions. Protons of energy ≥ 2 MeV had free access from interplanetary space to the magnetosphere and were not stably trapped outside of $L \sim 7.5$.

Voyager 1 traversed Saturn's magnetosphere during relatively quiet interplanetary conditions. The cosmic ray experiment (CRS) (1) complemented and extended the morphology of the outer magnetosphere reported by the Pioneer 11 investigators (2) to higher latitudes and to significantly different interplanetary conditions and provided the first information about the magnetotail at angles greater than 90° from the Saturn-Sun line. A detailed comparison between data from these missions is important for identifying the various processes that shape the Saturnian magnetosphere. The Voyager 1 CRS data presented here are restricted to the outer portions of the Saturnian magnetosphere [$L \geq 7.5$ (3)] where the instrument response to the very intense electron fluxes and very soft proton spectra was unambiguous.

Magnetospheric Morphology

Counting rates of protons with energies > 0.43 MeV and 1.8 to 8 MeV are shown in Figure 1. Also shown are corresponding normalized rates with similar energy thresholds observed on Pioneer 11 (4). Voyager 1 entered the magnetosphere three times between 23.7 and 22.9 Saturn radii (R_S) (5). Enhancements in the > 0.43 MeV proton flux were observed at each entry into the magnetosphere. Since no similar flux enhancements were observed during the passages back out of the magnetosphere, the enhancements were more likely the result of a transient increase in proton intensity associated with the expansion of the magnetosphere rather than the result of a permanent layer at the magnetopause. Thus the enhancements observed within the magnetosphere at

22.0 and 21.6 R_S (4th and 5th peaks) may also have been due to continued radial oscillations of the magnetopause.

The > 0.43 MeV proton flux observed by the Voyager 1 CRS experiment was more intense and peaked farther from Saturn than the > 0.55 MeV proton flux measured on Pioneer 11 (Fig. 1). These differences were at least partly due to the different threshold energies and different latitudes of the spacecraft's trajectories, although the Voyager data suggest that the flux decrease near $L = 9$ may be attributable to absorption by Rhea. Additional analysis will be required to determine the relative importance of these effects.

Within the magnetosphere the proton differential energy spectra, $j(E)$, (insets to Figure 1) are well represented by the sum of two components,

$$j(E) = K_1 E^{-\gamma} + \frac{K_2}{\sqrt{E}} \exp(-\sqrt{E/E_0}) ,$$

where E is the proton kinetic energy, K_1 and K_2 are constants, γ is the power law index, and E_0 is the characteristic energy corresponding to the e-folding momentum. This two component spectrum suggests two different sources for these protons. The exponential component was similar to the pre-encounter interplanetary proton spectrum and remained almost unchanged into the outer magnetosphere and tail regions (Fig. 1), while the power law component was of magnetospheric origin with $\gamma \sim 7$ on the inbound pass ($L > 12$), a value that is within ± 1 of those observed on Pioneer 11 (4).

At energies above 1.8 MeV, where the magnetospheric component was negligible, the proton flux observed by Voyager 1 was constant from interplanetary space into $L \sim 7.5$. A high energy component was also observed both inside and outside the magnetosphere by Pioneer 11 (4), but it was over an order of magnitude more intense and corresponded to the higher interplanetary flux at that time. Together, these observations provide strong evidence that interplanetary protons above 1.8 MeV had free access to the Saturnian magnetosphere at rigidities well below the dipole Störmer cutoff value via the magnetotail or other field distortions (4) and thus that protons of energies ≥ 2 MeV were not stably trapped outside $L \sim 7.5$.

The radial dependences of the electron intensities (Fig. 2) were similar to those at comparable energies observed on Pioneer 11 (4), except that at electron energies > 0.6 MeV on the outbound pass the Voyager 1 electron flux remained nearly constant from $L \sim 7$ to 9. Outbound at $L \sim 10$, a rapid decrease in the electron flux and an accompanying decrease in the > 0.43 MeV proton flux signaled a transition, perhaps from the stable trapping region to a quasi-stable trapping region. Beyond $L \sim 10$ the magnetic field direction indicated the onset of the magnetotail (5), and between $L = 10$ and 25 the low energy electron and proton fluxes both showed large time dependent variations. The rapid flux increase at $L \sim 14$ may have been the result of a change in interplanetary conditions. Plasma measurements on Voyager 2, when extrapolated to the position of Saturn, indicate that

the solar wind pressure should have doubled sometime while Voyager 1 moved from $L = 14$ to $L = 26$ (6). Minima in the fluxes of both protons and electrons, at $L = 17$ to 20 show a correlation with Titan's orbit, which may be coincidental. The proton spectrum of this tail population was extremely soft, with $\gamma = 9$ to 10 .

Voyager 1 traversed the magnetotail between 25 and $\sim 45 R_s$ (Fig. 3) at a latitude $> 20^\circ$ and a local time of ~ 0300 hours. An appreciable flux of electrons (0.15 to 0.4 MeV) was observed over most of this period (Fig. 3), while the proton flux had dropped to near interplanetary values. The relatively intense electron flux observed at these latitudes demonstrates that these electrons were not confined to an equatorial current sheet. This contrasts with the Jovian magnetotail and may result from a less distended field configuration. Tailward-streaming bursts of > 0.43 MeV protons were observed sporadically throughout this region.

The Saturnian magnetotail is probably the key to the properties of the outer magnetosphere. In Saturn's magnetotail, as at Earth and Jupiter, changes in the tail configuration induced by interplanetary disturbances may lead to the acceleration of both ions and electrons to several hundred keV. The Titan hydrogen torus (7) is a likely source of these ions, which are then further energized as they diffuse inwards through the conservation of the first and second adiabatic invariants (8). This process would thus provide a natural explanation for the larger

proton-to-alpha ratio observed in the Saturnian magnetosphere (4) compared to the ratio observed in the interplanetary medium.

Energetic charged particle absorption by Rhea and Titan

Voyager 1 crossed the orbits of Rhea and Titan at longitudes close to those of the moons. Localized decreases in the charged particle intensity were observed which resulted from absorption of the trapped radiation by the moons. Figure 4 shows the absorption signature observed in five independent counting rates just outside $L = 8.5$, significantly inside the $L = 8.8$ dipole L-shell of Rhea. Despite the apparent discrepancy in position, this feature was almost certainly due to Rhea as it was the only signature observed in this region. The widths at half minimum of the absorption feature observed by the LET detectors were ~ 3000 to 4000 km, which is what would be expected for absorption by Rhea [765 km radius (9)] of 0.5 MeV protons which had gyroradii in this region of ~ 3500 km.

Over the time period shown in Figure 4 Voyager 1 was $\sim 1 R_s$ north and $\sim 4^\circ$ east of Rhea; thus it took the magnetospheric plasma ~ 7 minutes to corotate from Rhea to Voyager 1. Since protons drift to the east, in the same direction as Saturn's rotation, protons observed at this time had passed Rhea less than 7 minutes earlier (~ 3 minutes for 0.5 MeV protons). Electrons drift in the opposite direction, however, and thus must have passed Rhea more than 7 minutes earlier. In a dipole field, electrons with energies > 0.58 MeV (at 60° pitch angle)

have drift velocities greater than Rhea's orbital velocity relative to the magnetospheric plasma and, thus, the absorption signature in these electrons would be on the other side of Rhea. Therefore the absorption feature observed in the TET electron counting rate must have been due to electrons with energies just below the nominal 0.60 MeV threshold.

Given that this absorption feature was due to Rhea, the position of the feature may be used to infer the magnitude of the non-dipole deformations of Saturn's magnetic field near $9 R_S$ at a local time of 0200 hours. Since charged particles closely follow magnetic field lines during their latitudinal bounce motion, the Rhea flux absorption feature provides a tracer of the field lines which pass the position of Rhea in the equatorial plane. The distortion of the field which is inferred by this method is illustrated in Figure 5. The points labeled along the Voyager 1 trajectory indicate the observed (a) and expected (b) positions of the Rhea absorption feature based on a magnetic dipole model. Dashed curves show the shapes of two dipole field lines and the solid line demonstrates a plausible distorted field line as implied by these observations. The magnitude and direction of this inferred deformation are consistent with the amount of non-dipolar distortion of the field measured by the Voyager 1 magnetometer at this time (5). Such a distortion could be produced by an equatorial current in the Saturnian magnetosphere or by a magnetotail neutral sheet current.

Since protons mirroring off the equatorial plane have a significant probability of missing Rhea, the depth of the absorption signature

depends on position and pitch angle. The ~ 3 minute separation between Voyager 1 and Rhea was about one bounce period for 0.5 MeV protons. Thus Voyager 1 passed behind Rhea where the 0.5 MeV proton flux was locally most heavily absorbed. The distance behind Rhea at which the absorption is most complete depends on pitch angle through the pitch angle dependence of the bounce and drift periods.

In contrast to the situation at Rhea, the Voyager 1 close approach to Titan provided the opportunity to observe charged particle absorption at distances smaller than the local 0.5 MeV proton gyroradius [$\sim 20,000$ km in a 5 nanotesla magnetic field (5)]. The large decrease in the LET B proton flux (Fig. 6b) centered at 5:42 spacecraft event time has a natural interpretation as a "shadow image" of Titan, formed as Titan intercepted the field of view of the LET B detector. The > 0.43 MeV proton fluxes measured by each of two other detectors which did not view Titan (Fig. 6c) show no statistically significant absorption. Each of these detectors was oriented $\sim 80^\circ$ from the spacecraft-Titan direction and neither was pointing within 35° of the equatorial plane. Thus no proton "shadow" due to Titan would have been expected in these detectors. In addition, Titan's effect on the observed electron flux should be different from its effect on the protons because of the smaller electron gyroradius (~ 460 km at 0.35 MeV). However, data gaps in the electron counting rate (Fig. 6b) do not permit detailed analysis.

The dashed curves overlaid on the LET B proton flux show the absorption profile which would be observed due to the shadow of Titan

on an otherwise isotropic proton flux. The upper curve was calculated assuming a radius for the absorber of 2860 km, the visible radius of Titan (10), while the lower curve, which provides a better fit to the data, was obtained assuming a radius of 3800 km, nearer the top of Titan's atmosphere (7). Since the model used to calculate the absorption profile assumed an isotropic proton flux, an anisotropic flux with a maximum near 90° pitch angles, as suggested by our data, will result in some overestimate of Titan's effective absorption radius.

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 2. Collections of earlier results from the Pioneer 11 encounter with Saturn are to be found in the "Saturn" issues of: Science 207, No. 4429 (1980) and J. Geophys. Res. 85, No. A11 (1980).
 3. L is defined here as $R/\cos^2\lambda$, where R is radial distance in Saturn radii ($1 R_S = 60,000$ km) and λ is latitude, which is accurate for a dipole field.
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Figure Captions

Figure 1. Proton intensities versus L and proton spectra in Saturn's magnetosphere. Curve 1 gives the counting rate of > 0.43 MeV protons from Voyager 1, and curve 2 gives a similar Pioneer 11 rate (> 0.55 MeV) which has been normalized to the geometric factors of the Voyager instrument. Curve 4 shows the Voyager 1 flux of 1.8 to 8 MeV protons (right-hand scale), and curve 3 shows the Pioneer 11 1.6 to 5 MeV proton flux. On the inbound pass, the magnetosheath extends to $L \sim 24$ and is indicated by shaded areas near the magnetopause crossings, which are identified by MP, with the Pioneer 11 symbol enclosed in a circle. Voyager 1 latitudes are shown above the distance scale. Pioneer 11 remained within $\pm 5^\circ$ of the equator. Proton spectra are shown in the insets. The power law index, γ , for the low energy end is given, as well as the characteristic energy E_0 for the high energy end. Pre-encounter spectra were almost indistinguishable from the tail spectrum at $L = 29$.

Figure 2. Electron intensities versus L in Saturn's magnetosphere. The Voyager 1 data in curves 1, 2, 4, and 6 correspond to electron energies of 0.15 to 0.4 MeV, > 0.35 MeV, > 0.60 MeV, and > 2.6 MeV, respectively. Curves 3 and 5 give Pioneer 11 rates for energies above 0.25 and 2.0 MeV, respectively, normalized to the geometric factors of the Voyager instrument. Magnetopause crossings are indicated by MP with the Pioneer 11 symbol enclosed in a circle. Near the magnetopause the magnetosheath is indicated by the shaded area.

- Figure 3. Voyager 1 electron and proton intensities in the magnetotail at northern latitudes between 20° and 23° versus distance from Saturn. Shaded areas indicate periods when Voyager 1 was in the magnetosheath.
- Figure 4. Counting rates of five CRS detectors on Voyager 1 in the vicinity of Rhea along the outbound pass versus spacecraft event time (SCET). "LET A", "LET B", and "LET D" label counting rates of essentially identical detectors which respond to protons > 0.43 MeV and have a low electron detection efficiency. The differences between LET A, B, and D counting rates are roughly consistent with the expected unidirectional anisotropy due to Saturn's rotation. "HET 2" and "TET" label counting rates of detectors with nominal threshold energies for electron detection of 0.35 MeV and 0.60 MeV, respectively.
- Figure 5. The Voyager 1 trajectory near Rhea with an illustration of the distortion of the magnetic field inferred from the Rhea absorption feature (solid line) compared to the shapes of dipole field lines in this region (dashed lines).
- Figure 6. (a) The Voyager 1 trajectory in Titan-fixed coordinates projected onto Saturn's equatorial plane. The distance scale is chosen such that the bottom time scale also labels spacecraft event time (SCET) along the trajectory.
(b) The flux of > 0.43 MeV protons measured by the LET B detector which looked towards Titan in the direction of the arrows shown along the trajectory trace in the upper panel

versus SCET, and the counting rate of electrons > 0.35 MeV versus SCET. Samples of the electron counting rate were obtained only in alternate 6.4 minute intervals. Vertical dashed lines define the interval when Titan covered the center of the LET B field of view. Heavy dashed curves drawn over the LET proton flux show the calculated Titan absorption signature in LET B for an isotropic proton flux assuming absorption radii of 2860 km (upper curve) and 3800 km (lower curve). (c) Fluxes of > 0.43 MeV protons measured by the LET A and LET D detectors versus SCET.

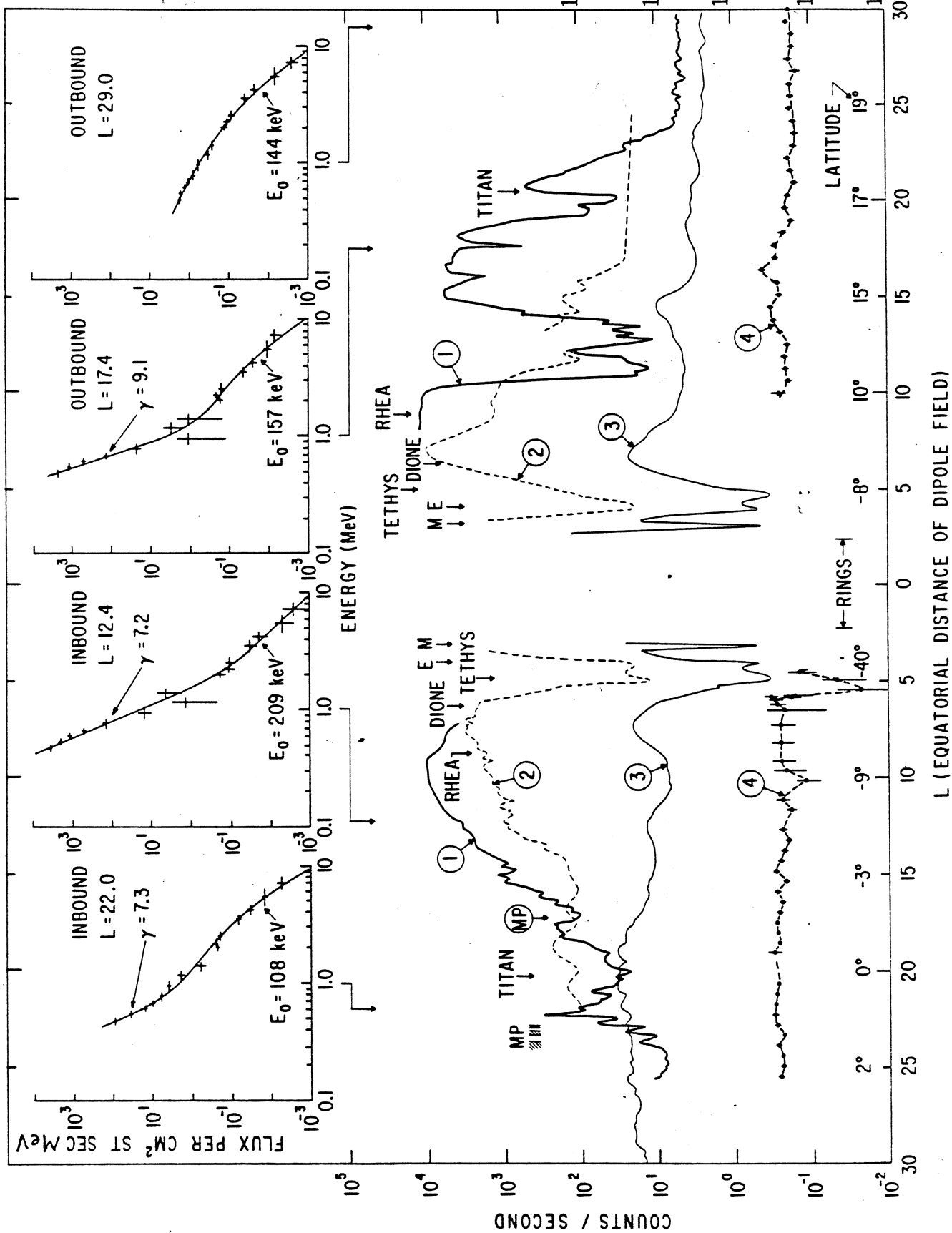


Figure 1

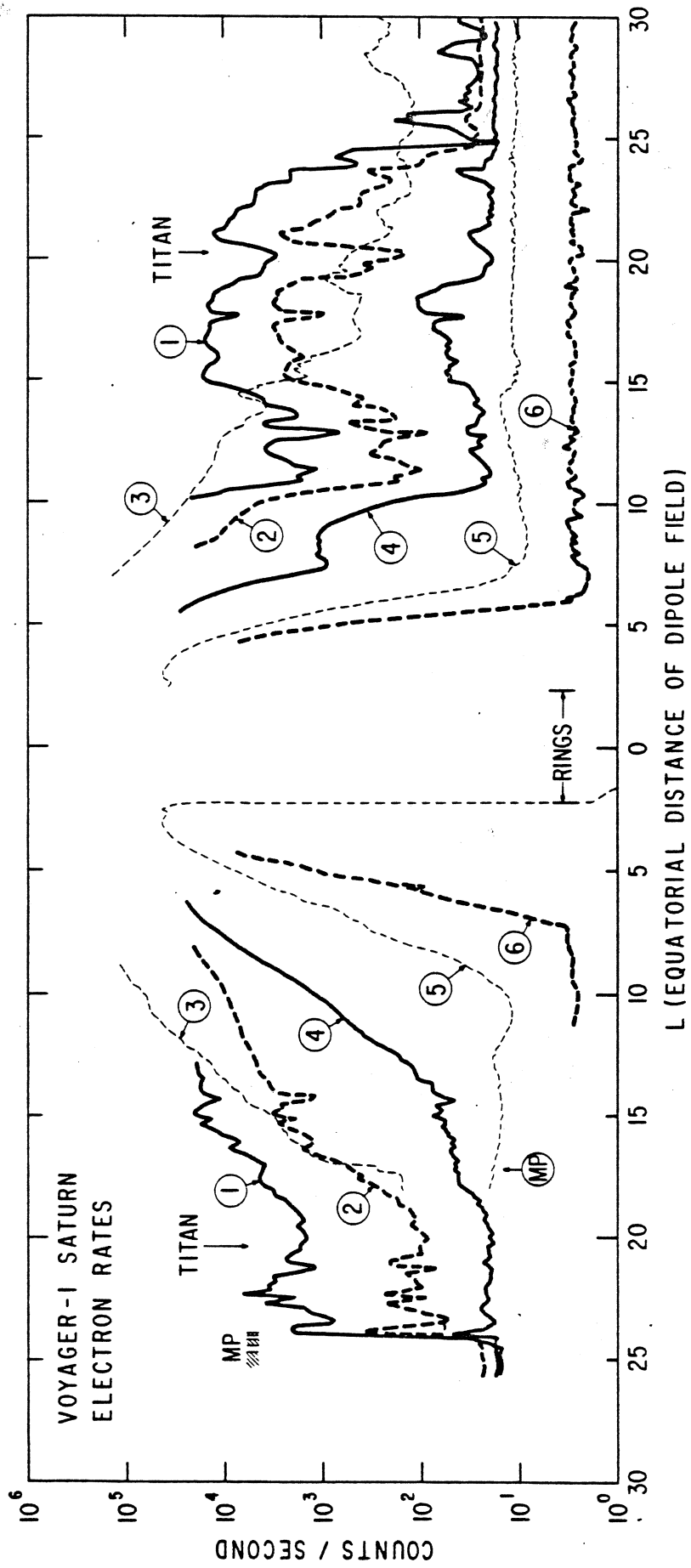


Figure 2

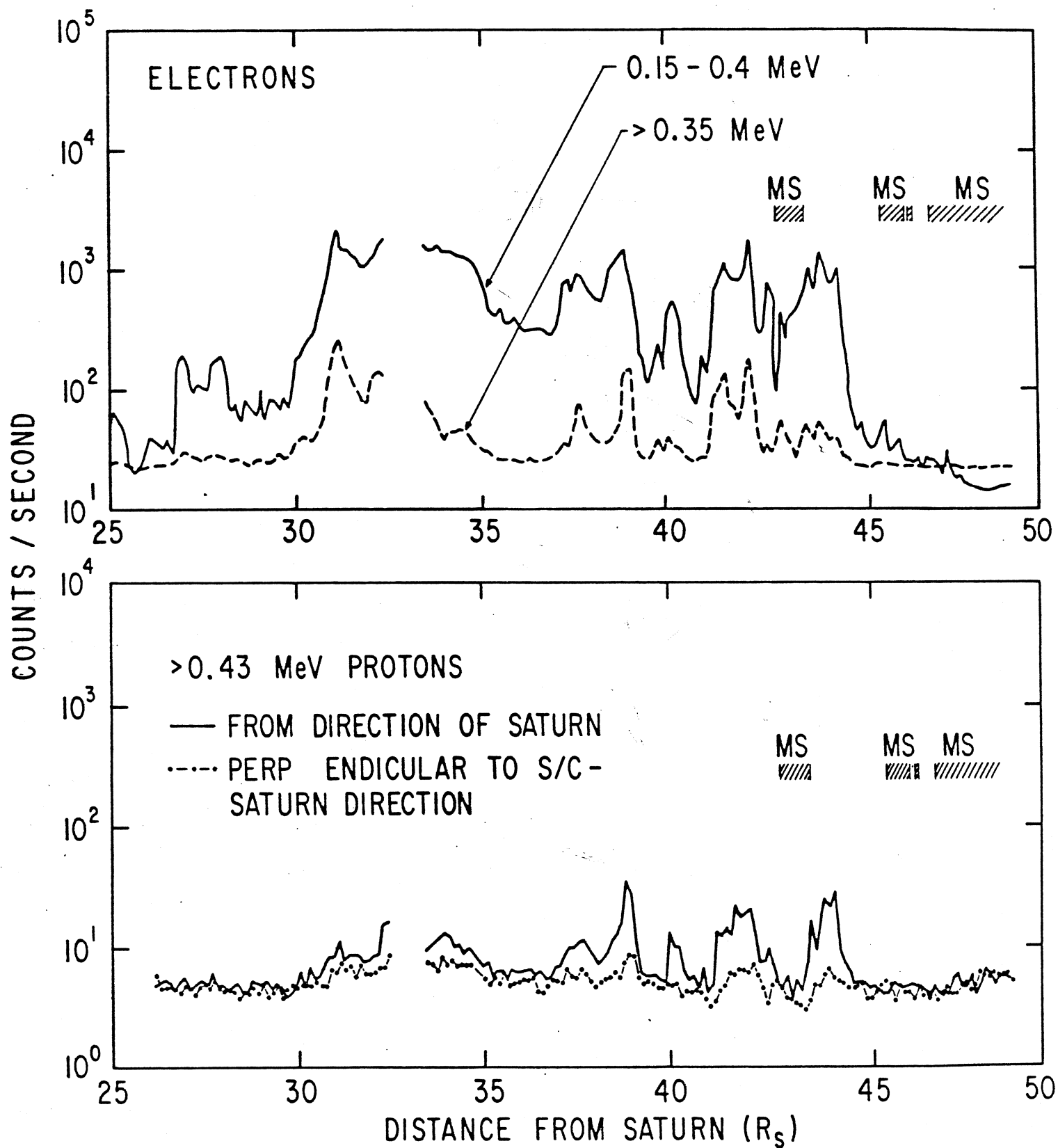


Figure 3

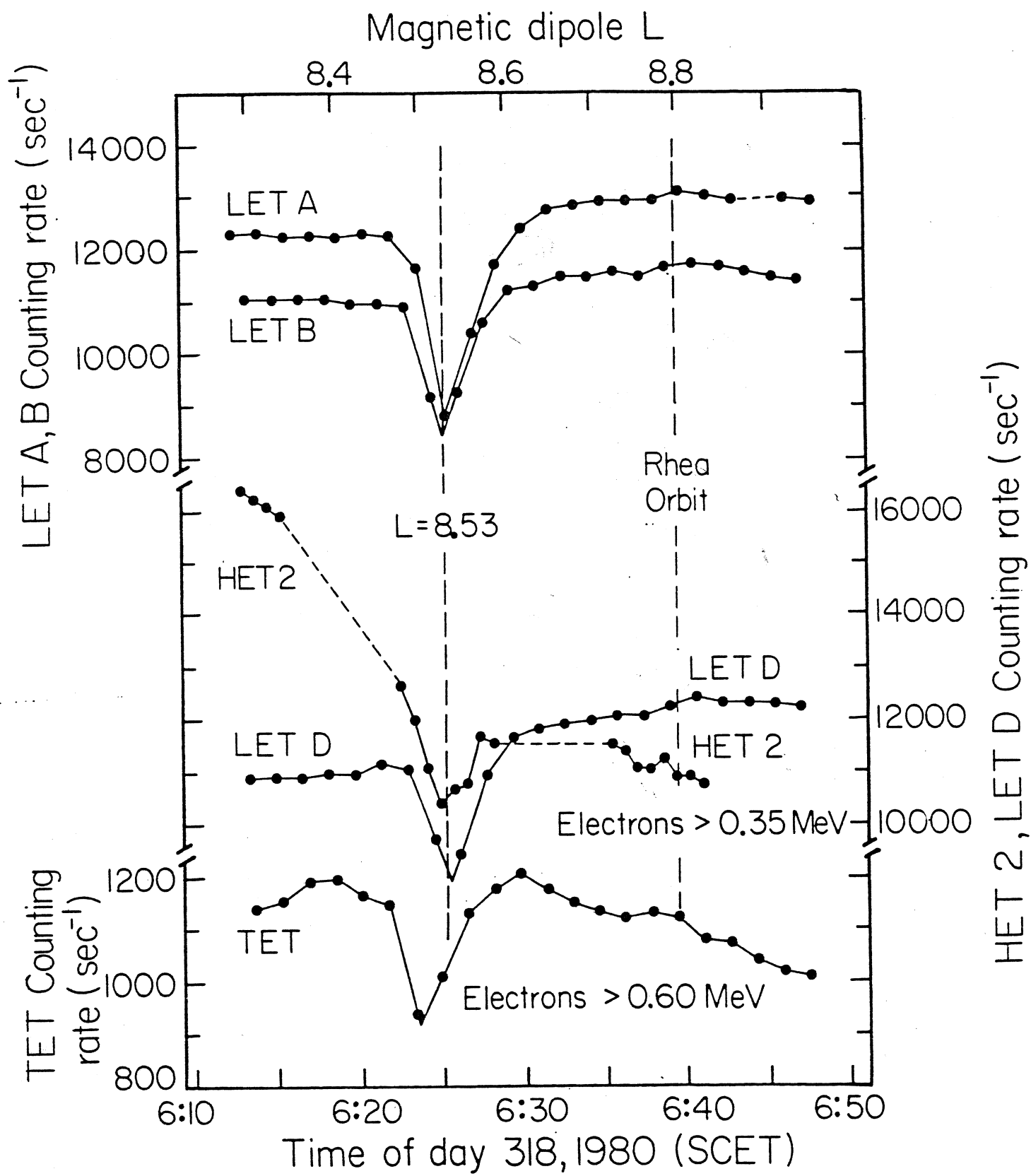


Figure 4

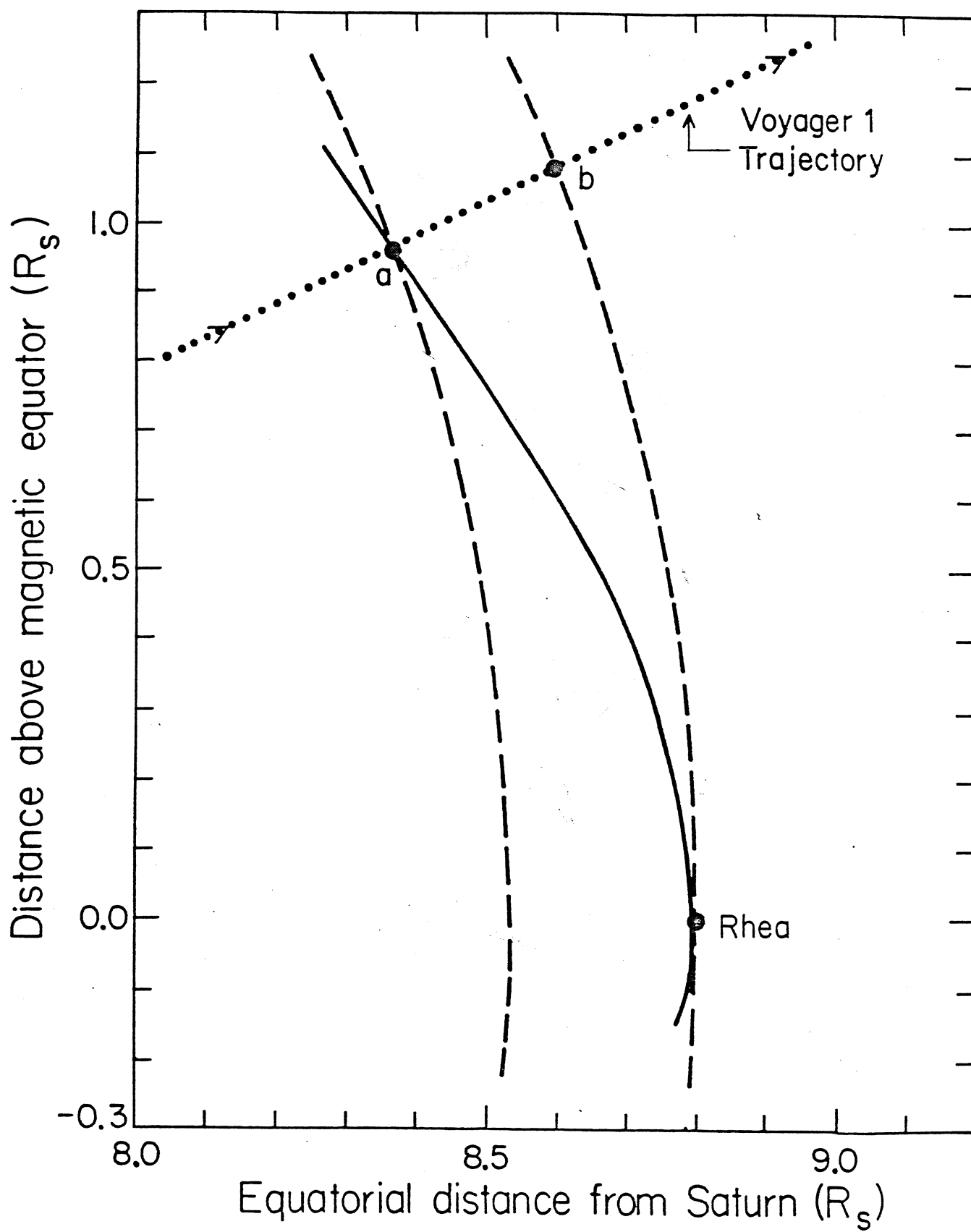


Figure 5

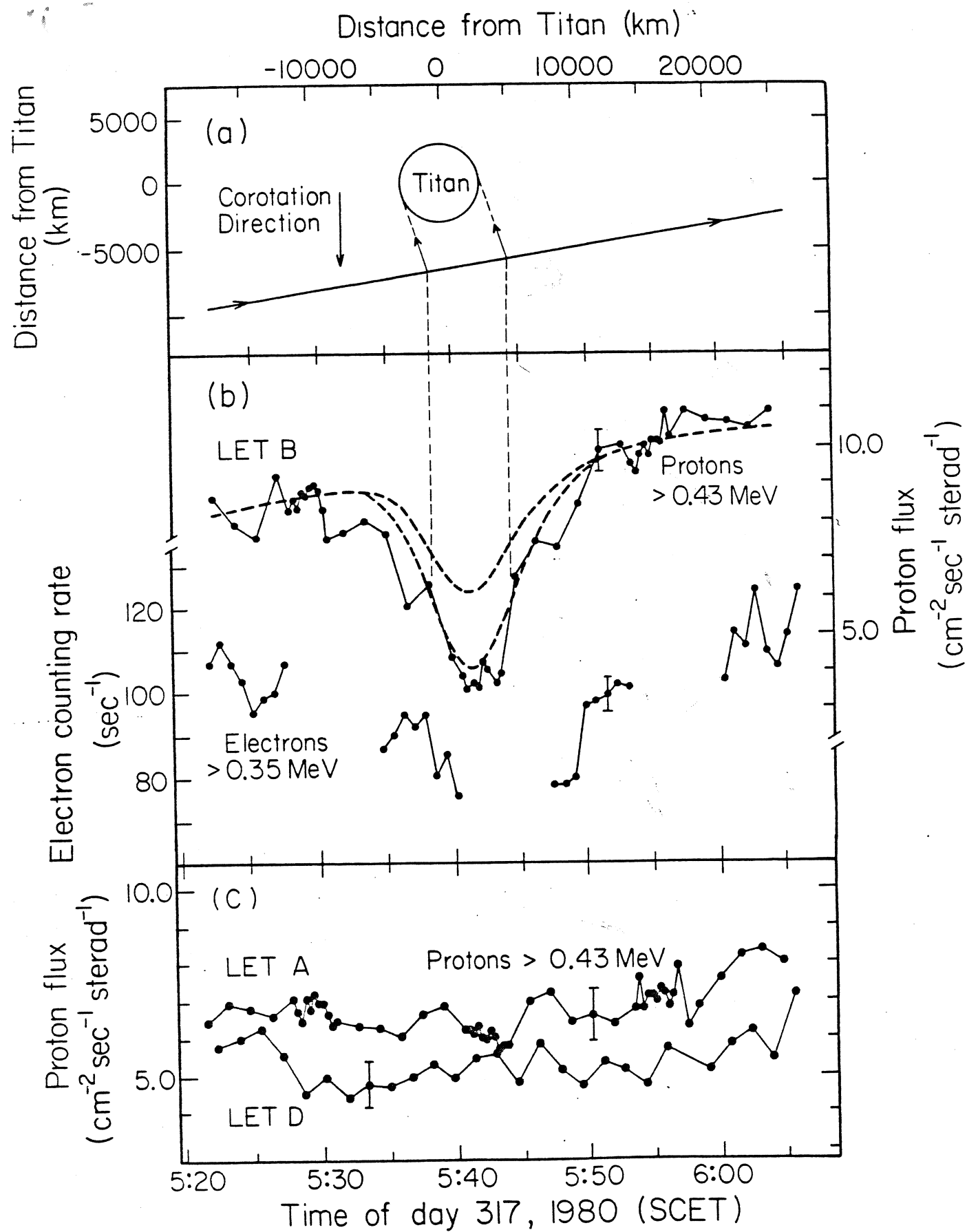


Figure 6